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A REACTION ATTITUDE CONTROL SYSTEM FOR JET VTOL RESEARCH AIRCRAFT

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16. Abstract

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     The combination of concepts of a rapid switching valve and a low torque nozzle permit maximum flexibility in system design of reaction attitude control systems for jet VTOL research aircraft.

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A REACTION ATTITUDE CONTROL SYSTEM FOR JET

VTOL RESEARCH AIRCRAFT

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SUMMARY

A new dual reaction control system provides the means for flight research on the requirements for VTOL attitude control systems. There are two conflicting requirements for any control system used in flight research. One is flexibility and the other is safety. Maximum flexibility can best be achieved by an electrically driven control system, but this frequently degrades safety. Maximum safety is provided by a mechanical control system, but this type system is difficult to change or adjust. Pilots consider their safety is not endangered if it is possible to switch from an electrical drive system to a mechanical drive system in about 0.1 sec after an electrical failure. The new dual reaction control system satisfies this requirement with a fail safe air switching system that controls 8.5 lb-m/sec of 500° F air. The research control system is an electrical drive system.

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The combination of concepts of a rapid switching valve and a low torque nozzle permit maximum flexibility in system design of reaction attitude control systems for jet VTOL research aircraft.

INTRODUCTION

For several years, Ames Research Center has been studying the effects of variable control power and of stability augmentation on the handling qualities of deflected-jet, fixed-wing VTOL aircraft. The flight tests used a control system, described in reference 1 (NASA TN D-2700), that was installed in the X-14A aircraft and consisted of two sets of reaction control nozzles: one set driven mechanically by the pilot's controls, and the other set driven by electric servomotors which are commanded by preselected combinations of

electrical signals generated by the pilot, rate gyros, or other signal sources. The disadvantage of this system is that the range of control forces available from the reaction controls is only a portion of that potentially available, since air is ejected from both sets of nozzles at all times even though only one set is desired for control. A research program was initiated to improve the performance of this control system in terms of increasing control power while continuing to ensure pilot safety.

The new dual-system attitude control concept involves the use of an air-switching valve to switch all the reaction control air into the desired system (electrically or manually driven) while none of the pilot's normal mechanical linkages are altered. Both mechanical and electrically driven systems respond to the input commands, but only the system with air in it will have any effect. Thus, a flexible and independent electrically driven system may be achieved with the mechanically driven system available for safety.

An additional area of research was associated with development of a reaction control nozzle having a low driving torque while delivering high reaction force, thereby providing high reaction control power and good control system response with lower power servo-drive motors.

AIR SWITCHING

As has been pointed out, it is a great advantage in control system research to have a flexible control system, which implies getting away from mechanical linkages and operating on electrical signals from various sources. Such an electrical system can be easily changed by the pilot, even in flight if desired, by simple knob adjustments and can be switched on and off at will. However, there is some reluctance to depend on an all-electric system when a pilot's life is at stake because faults do occur in components and wires break or short. If such a failure occurs, it is desirable to have a mechanical backup system that can be used to land the aircraft safely. In VTOL flight tests, the time to switch to the mechanical system must be very short, and automatic sensing may even be required so that disastrous rates or attitudes are not built up before the pilot can decide there is trouble and can react.
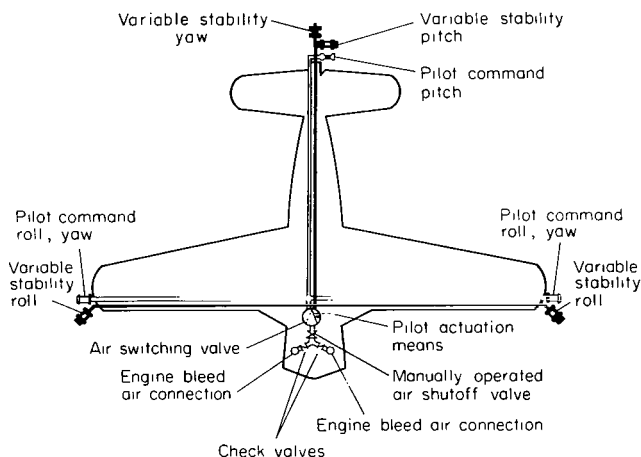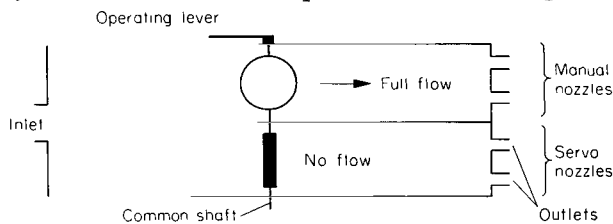
A concept that can be used for a dual system is to switch all the bleed air, as indicated in figure 1, from one set of reaction nozzles, driven electrically, to another set, driven mechanically. Thus, the air is flowing entirely in an electrically driven set of nozzles during the research tests and can be switched into a mechanically driven set for safety in landing or

Figure 1.- New air distribution system.

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maneuvering. This arrangement has the advantage of not changing any of the mechanical linkages of the pilot's controls. It also permits the reaction force in the mechanical system to be distributed differently from that of the electrical system. The pilot has full control power available in the reaction nozzle set that has air flowing in it. Of course, the other nozzle set moves in response to whatever signals are given it without producing any reaction. A disadvantage of such a system is that the introduction of a single air switching valve reduces the reliability of the overall system and adds some weight.

The requirements for such an air switching valve, both for operation and safety, are: (a) fast release from the electrical system and fairly fast engagement to the electrical system; (b) remote control, by pilot, of release; (c) adequate size of valve for system flow requirements but with minimum weight, space, and power usage; (d) positive indication to pilot of valve position; (e) fail-safe characteristics so power failure returns it to the mechanical system position; (f) high reliability of operation; and (g) constant air flow for both valve positions to maintain constant bleed from engines.

Valve requirements, selected on the basis of analysis, simulation, past experience, and pilot preference included: (a) release time, as established by simulation with pilots in a single axis loop, to be 0.1 sec or less, engagement to be as fast as feasible, consistent with above, and not more than 1.0 sec; (b) valve to be sized so air flow of 8.5 lb-m/sec causes a pressure drop less than 3 psi; and (c) electrical latching in the electrical control position and a spring that will return the valve to the manual control position if electrical power is interrupted.
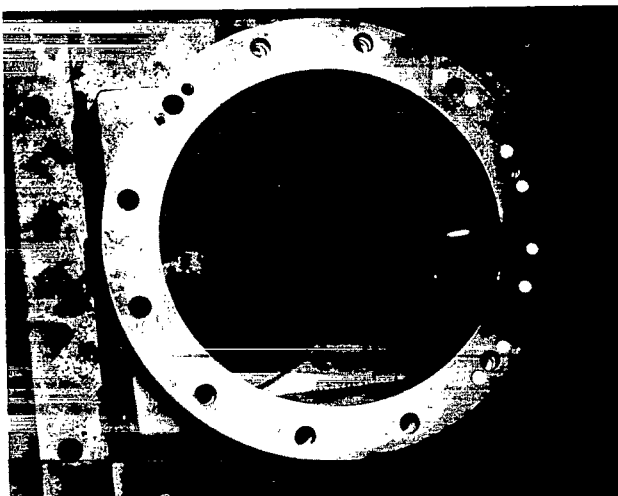

Sketch (a)

Figure 2.- Dual butterfly of switching valve (from inlet side).

Consideration of the above requirements suggested a dual butterfly valve with single inlet and a double chambered outlet. The two butterflies are on a single shaft and at right angles to each other, so that one is fully shut the other is fully open (see sketch (a) and fig. 2). The flow from each of the outlet chambers is divided between wing and tail distribution ducts. The requirement of a controlled return to the manual mode is met with a solenoid-actuated latching mechanism and constant torque spring.

Before a means of actuation could be selected or spring stiffness

□ Pressure reset at each position
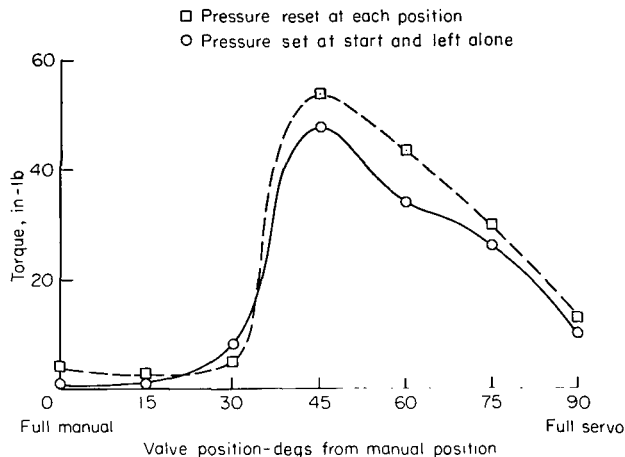○ Pressure set at start and left alone

Figure 3.- Torque characteristics of final valve under 50 psig pressure.

determined, the torque caused by air flow had to be measured on a prototype valve. Typical results for the final valve design are shown in figure 3. The difference between the curves of this figure is due to greater total flow in the valve when both passages are partially open. This greater flow drops the pressure which, in turn, reduces the torque required. Notice that the valve will tend to return to the manual position without requiring any external spring force, probably because of the way the inlet passages were laid out.

A spring was chosen to augment the inherent torque on the valve. Since the torque required to hold the valve in any position for the maximum operating pressure expected was known, a nominal spring torque was chosen to provide additional acceleration for the mechanism. The spring used is a special type that produces the same torque for all deflections, and one or more units may be easily combined to increase the torque. The electrical circuit to hold the valve in the full servo position and provide release includes only the solenoid and release button of figure 4.
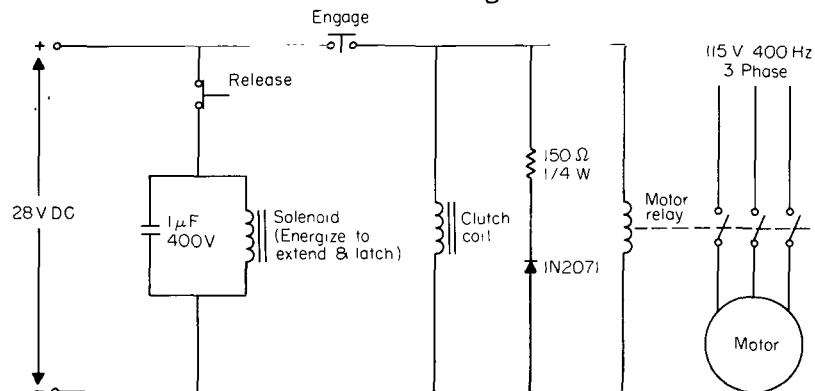

Figure 4.- Circuit used for test.

The final configuration of the air switching valve followed simple design concepts and had no critical mechanical clearances or adjustments, even under the expected operating temperature. Both valve ports are the same size and have low restriction to flow. The shaft is assembled through the butterfly disks and fastened to them by a key, and the shaft secured by a nut. At the other end of the shaft, a spline is provided for the operating lever. Figure 5 shows some of the mechanical details.

A final test was made in the Ames structural dynamics laboratory where large amounts of air could be discharged safely. This air was cold, but tests of the valve without air but at 500° F gave no indication of binding or
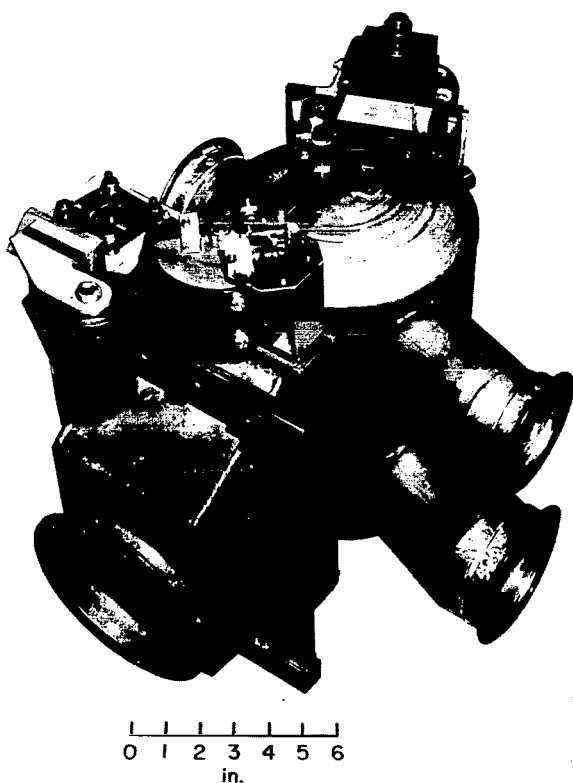
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other problems. It was found that a spring torque (using one spring) of 42 in.-lb gave a release time of approximately 0.09 sec. For the actual aircraft installation, the spring was split into two parallel parts, separately mounted for mechanical redundancy (one-half of spring will return the valve to manual). During these testing sequences the switching valve was operated several hundred times, which is estimated to be equivalent to six months or more of actual usage on the aircraft. There has been no indication of any type of failure.

Figure 5.- Switching valve with spring and limit switch details.

REACTION CONTROL NOZZLES

The reaction control nozzles produce variable control moments about the roll, pitch, and yaw axes of the aircraft by modulating the flow of engine bleed air. As was pointed out earlier, there are two sets of nozzles - one set is mechanically driven by the pilot; the other is servo-driven. The servo-driven nozzles described in reference 1, discharge air from diametrically opposed variable orifices. The exit areas are controlled by rotary valve motion. There are four servo-driven nozzles - one each for pitch and yaw control at the tail, and one at each wing tip for roll control. In the present study it was desired to enlarge the nozzles so that they could control the additional air made available by the air switching concept and to devise a type of nozzle for the wing tips that could be either double opening or single opening.
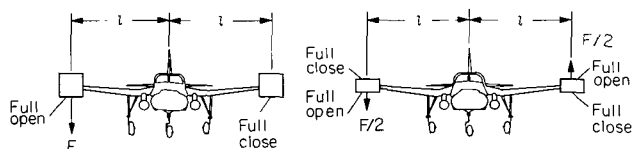
Design Constraints

Several constraints are placed on the design of reaction control nozzles. Jet engine characteristics require that the amount of bleed air be held roughly constant; this implies that the net exit area of the reaction control system should be held constant. Furthermore, proportional control is desirable; therefore, the reaction force produced should be a linear function of the command signal. The weight of the nozzle and servo actuator packages should be kept low since their location (at the extremities of the aircraft) makes them potent contributors to aircraft moments of inertia. For compatibility with a servo-drive motor actuator, the valve motion should be rotary;

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and, in order to minimize the size of the servomotor, the torque required to drive the nozzle should be kept low. Rapid response of the nozzle (e.g., 0.1 sec to open fully) is essential to avoid introducing delays into the aircraft response to pilot commands.

Development and Test

Dual exit versus single exit- A basic difference between dual exit and single exit nozzles is their ability to satisfy the constant net exit area constraint. A dual opening nozzle has diametrically opposed variable orifices such that as one orifice opens the opposite orifice closes by the same amount, thus maintaining a constant total exit area. A single opening nozzle cannot in itself satisfy the constant area constraint. Therefore, if single exit nozzles are used they must operate in pairs, one opening as the other closes. Since there is but one nozzle per axis in the pitch and yaw axes, these nozzles must be double opening. The roll nozzles may be single or double opening because they operate as a pair, one at each wing tip.

The advantage of single exits for the roll nozzles is that air ported through them downward adds lift to the aircraft. (In the case of the X-14, this additional lift may amount to as much as 200-220 lb.) However, if the extra lift is not needed, it can be a disadvantage since thrust must equal weight to maintain hover in a VTOL aircraft. Consider a fixed weight aircraft which has sufficient thrust to hover. If a lift increment is added by single exit nozzles, then main engine thrust, hence engine rpm, must be reduced to maintain hover. Reducing engine rpm reduces the amount of bleed air available. Thus, a single exit nozzle in this situation yields less control power than a double exit nozzle would. Furthermore, if duct losses are not to increase, the single exit system will require larger diameter air ducts since for a hard-over command all the air must be ducted to a single wing-tip nozzle (see fig. 6). In the double exit case, half the air goes out each wing-tip nozzle. The greater air flow through a single nozzle also requires that the orifices be larger than those of their double exit counterparts. Because of their size and also because of flow conditions, the single exit nozzles require a higher driving torque.

(a) Single exit nozzles.   (b) Double exit nozzles.

Figure 6.- Hardover command in each type nozzle.

For the X-14 aircraft, a clear choice between the types was not possible because both lift and control power are critical items. Added lift permits increased fuel load and longer flights or more instrumentation. Higher available control power increases the aircraft's range of simulation. Hence, an experimental nozzle was developed which could be made with a single exit or with double exits, or as an intermediate version between these two extremes.

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(a) Nozzle stator can

Drive shaft

(b) Swinging elbow rotor

Domed end cap

Drive shaft

(c) Inside can rotor

Drive gear

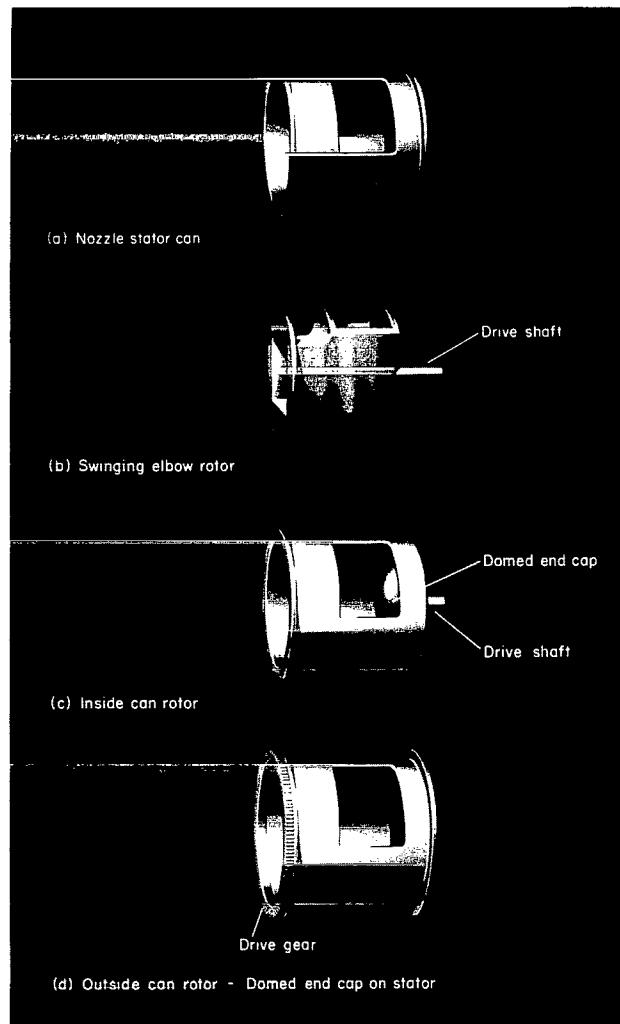(d) Outside can rotor - Domed end cap on stator

Figure 7.- Experimental nozzles.

Experimental nozzle development- Several different nozzles were designed, built, and tested. All models featured a cylindrical body stator with an exit orifice or orifices cut into it. Primary differences between models were in the form of the rotating element (rotor) which adjusts the size of the exit orifice (see fig. 7). The swinging elbow and the inside can rotors both slip inside the nozzle stator can. The outside can rotor slips over the nozzle stator can. The low-driving torque requirement proved the decisive factor among these since all types had essentially the same reaction force per unit exit area. The exit areas and nozzle diameters were identical in all models to permit a fair comparison.

Single exit nozzles- The outside can required the lowest driving torque and the swinging elbow required the highest driving torque. This torque tends to increase the opening of the inside can and of the swinging elbow, and to decrease the opening of the outside can. Basically, the torque is produced by
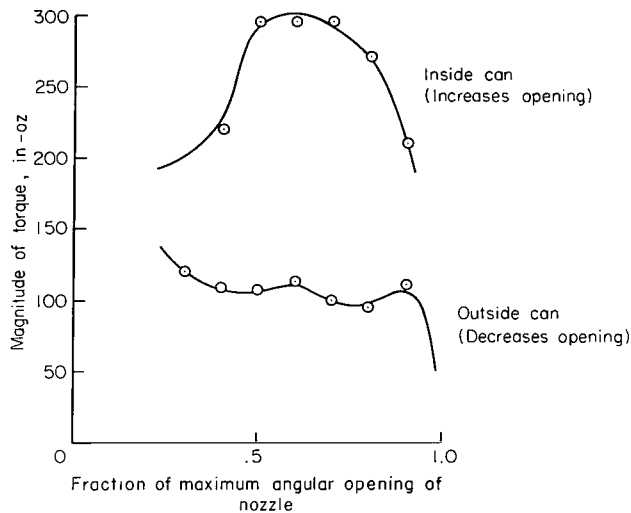
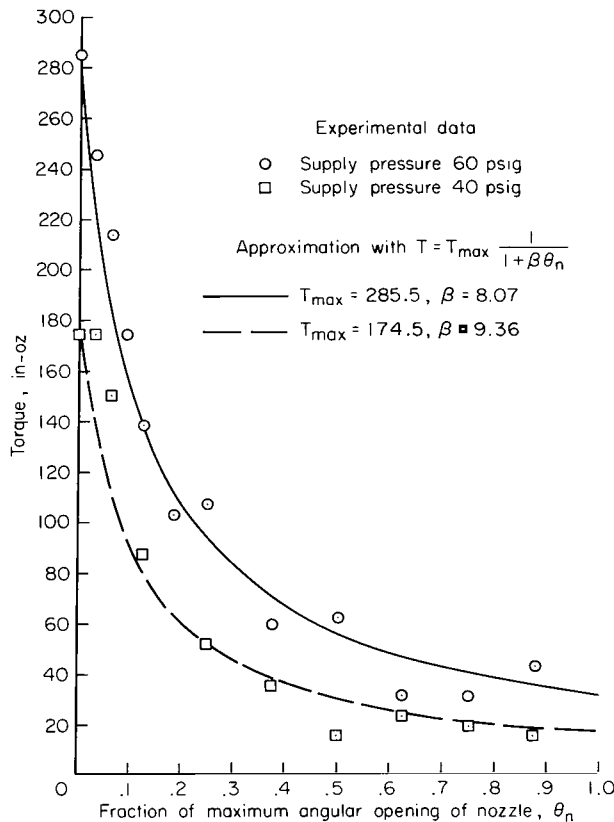Figure 8.- Driving torque characteristics of inside and outside can nozzles.

Figure 9.- Driving torque for the single exit nozzle (outside can).

a pressure differential acting on the rotor edges.[1] One edge of the exit port is exposed to the pressure in the exiting air stream; the opposite edge is exposed to either supply pressure (inside can and swinging elbow) or to atmospheric pressure (outside can). The pressure being different on opposite edges of the exit port produces a torque. There are secondary effects, however. Halving the wall thickness of the rotor does not in all cases halve the torque, and rounding or beveling the upstream edge of the orifice also affects the torque. The swinging elbow presents the largest area on which this differential pressure may act and therefore has the highest driving torque. Figure 8 demonstrates the superiority of the outer can configuration (particularly in the midrange of operation). This plot is based on experiments with a preliminary model at a source pressure of 60 psig, and 0.125 inch thick walls on the rotors. The stator diameter was 5.5 inches and the length of the exit port was 2.23 inches. Based on this data the inside can concept was dropped and further design concentrated on the outside can rotor configuration.

The characteristics of the final outside can nozzle are shown in figure 9. This version featured several design innovations that will be discussed later. The variation in torque with exit area is apparently caused by a variation in the pressure at the rotor edge in the air stream as the exit size is changed. The general form

$$T(\theta_n) = T_{max} \frac{1}{1 + \beta\theta_n} \qquad (1)$$

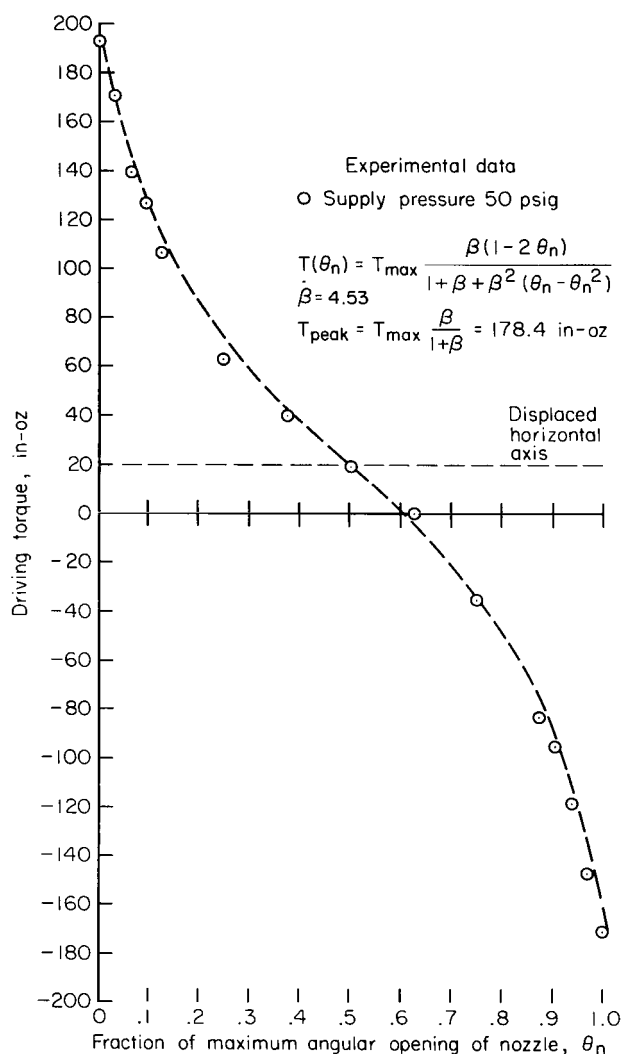[1]Reference 1 describes in more detail efforts made to establish the sources of such torques.

$$T(\theta_n) = T_{max} \frac{\beta(1 - 2\theta_n)}{1 + \beta + \beta^2(\theta_n - \theta_n{}^2)}$$

$$\beta = 4.53$$

$$T_{peak} = T_{max} \frac{\beta}{1+\beta} = 178.4 \text{ in-oz}$$

Experimental data

O Supply pressure 50 psig

Displaced horizontal axis

Driving torque, in-oz

Fraction of maximum angular opening of nozzle, θ_n

Figure 10.- Driving torque of the double exit nozzle (outside can).

may be used to curve fit the experimental data for the single exit outside can nozzle. In equation (1), $T(\theta_n)$ is the driving torque, T_{max} is the maximum driving torque, θ_n is the normalized angular opening of the nozzle ($\theta_n = \theta/\theta_{max}$, where θ is the angular opening of the nozzle and θ_{max} is the maximum angular opening), and β is a dimensionless constant adjusted to achieve a good match to the empirical data. The parameters T_{max} and β may be fixed by several techniques. The approximations shown in figure 9 are obtained by letting T_{max} equal the measured torque at near zero opening and computing an average β over the rest of the data points. This technique yields T_{max} = 285.5 in.-oz and β = 8.1 for the 60 psig case. Fitting equation (1) by a least mean square technique to the same data yields T_{max} = 300 in.-oz and β = 9.1. Nozzle parameters for these curves were rotor wall thickness 0.09 inch and length of exit port 1.75 inches for a 4.96-inch-diameter rotor rotating ±20° from its center position. The supply pressures are shown in the figure.

Double exit nozzles- The double exit version of the experimental outside can nozzle yielded the driving torque curves shown in figure 10. Note that the double exit torque curve seems to be a superposition or composite of two single exit curves. With the rotor in the center position, the torque contributions from the two sides approximately cancel each other, and as either top or bottom closes, the magnitude of the torque tends to increase. Tests of the mass flow rate versus exit area indicated that the nozzles were operating choked at the exit port over the range of angular openings used. Thus, it is reasonable that the diametrically opposite ports should have little influence on each other. A good fit to the curve of figure 10 is obtained by the superposition of two single exit characteristics (reflect one single exit characteristic about the line $\theta_n = 0.5$ and about the θ_n axis and add it to an unreflected characteristic). Performing this superposition with equation (1) [$T(\theta_n) - T(-\theta_n + 1)$] and simplifying the resulting expression yields equation (2):

$$T(\theta_n) = T_{max} \frac{\beta(1 - 2\theta_n)}{1 + \beta + \beta^2(\theta_n - \theta_n^2)} \qquad (2)$$

The parameters in equation (2) are the same as in equation (1), that is, referenced to one of the exits. It should be noted therefore that the peak of the double exit nozzle torque curve is not T_{max}, but rather $T_{max}\beta/(1 + \beta)$. The curve in figure 10 illustrates the application of equation (2). Since equation (2) is symmetrical about the point $\theta = 0.5$ and the experimental data are not exactly symmetrical, the following fit procedure was used. Exact fit was required at the point $\theta_n = 0.5$; therefore, a displaced horizontal axis was established which passed through the data point at $\theta_n = 0.5$. The average deviation of the torque at the two extremes ($\theta_n = 0$ and $\theta_n = 1$) from the new axis was taken as the peak torque $[T_{peak} = T_{max}(\beta/1 + \beta)]$ in equation (2). The deviations of the torque at other values of θ_n from the torque value at $\theta_n = 0.5$ were then used to calculate an average β. Torque values calculated from equation (2) on the basis of these parameters ($T_{peak} = 178.4$ in.-oz and $\beta = 4.53$) were used to plot the curve fit (fig. 10) with reference to the displaced horizontal axis. Nozzle physical dimensions were the same as in the preceding single exit case.

Mechanical Details

Structurally, the outside can nozzle design has several advantages. Figures 11 and 12 are photographs of the final double exit design. No bearings lie in the air stream and only the small bearing serves as a thrust bearing. The large bearing is only for rotation and low friction rotary spacing.
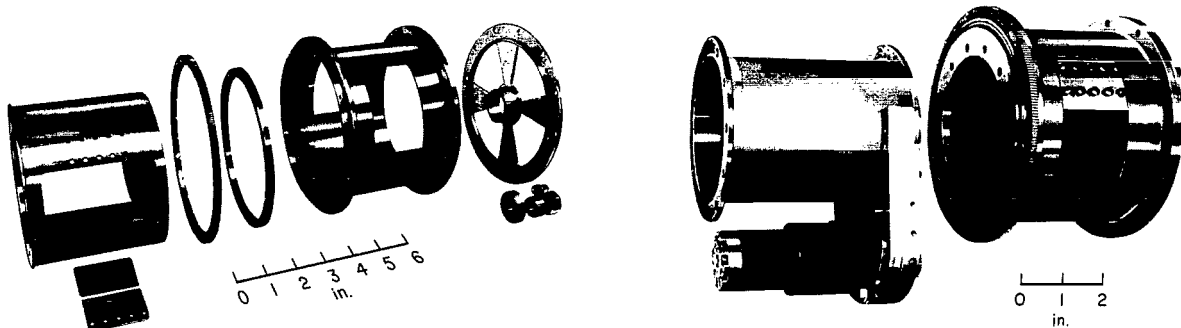

Figure 11.- Exploded view of double exit prototype. Figure 12.- Assembled view of double exit prototype.

The coincident edge feature (see fig. 13) eliminates thrust tangential to the nozzle body which results when the nozzle makes a noncoincident or "scissor-type" closing. Placing a large diameter drive gear on the rotor circumference reduces the number of gear passes required to drive the nozzle from a small,
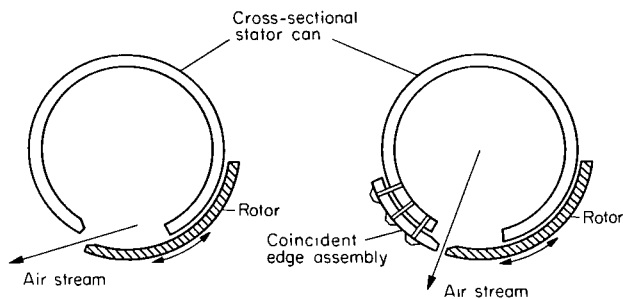
Figure 13.- Coincident edge feature.

high-speed, low torque servomotor, thus minimizing backlash in the servo-system. The upstream edges of the orifice are rounded since the experimental data (not shown) indicate that rounding improves the discharge coefficient of the nozzle by about 3 to 4 percent.

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        Moffett Field, Calif. 94035, Dec. 8, 1969

REFERENCE

1. Pauli, Frank A.; Hegarty, Daniel M.; and Walsh, Thomas M.: A System for Varying the Stability and Control of a Deflected-Jet Fixed-Wing VTOL Aircraft. NASA TN D-2700, 1965.

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